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LOADS INDUCED ON A FLAT PLATE AT A MACH NUMBER OF 4.5 WITH A SONIC OR SUPERSONIC JET EXHAUSTING NORMAL TO THE SURFACE

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LOADS INDUCED ON A FLAT PLATE AT A MACH NUMBER OF 4.5 WITH A SONIC OR SUPERSONIC JET EXHAUSTING NORMAL TO THE SURFACE

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SUMMARY

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An investigation was made to determine the pressure distributions on a flat plate with a sonic or a supersonic jet exhausting normal to the plate surface. Tests were made at a Mach number of 4.5 for a range of jet pressure ratios (that is, ratio of stagnation pressure of secondary jet to free-stream static pressure) and for various free-stream Reynolds numbers.

Based on a comparison of the ratio of the total reaction force of the test jet to the calculated reaction force of an isolated fully expanded jet (with mass flow equal to that of the test jet), the supersonic nozzle appears to be more effective for use as a control than the sonic nozzle. Total force as used herein is the calculated simple reaction force of an isolated nozzle plus the induced force resulting from the secondary-jet interference with the stream flowing over the flat plate.

The data also indicate that eliminating areas of negative pressure on the plate would cause an increase in effectiveness up to approximately 12 percent for either jet.

INTRODUCTION

The development of a simple and effective means of directional control of rocket-powered vehicles is a problem which has been the subject of a number of investigations. (See refs. 1 to 8, for example.) Currently such devices as control surfaces immersed in the rocket exhaust and swiveling nozzles are used for control. As the performance and size of rocket engines are increased, the problems which are associated with these types of control (erosion of controls, large complicated control hardware, etc.) will be compounded and other types of control may have to be devised.

In a number of reports the use of jet interaction has been suggested as a means of directional control. In this method, introduction of a secondary jet into the primary exhaust flow of nozzles creates a shock-wave system and a boundary-layer interaction and results in an asymmetric pressure field inside the rocket nozzle. This asymmetric pressure field creates a force perpendicular to the original primary thrust direction, which ordinarily is larger than would be obtained from the use of the secondary jet as a conventional isolated reaction control. The resulting pressure fields, as shown in reference 2, are such that ahead of the secondary jet the pressures increase and are the primary source of the induced side force. Behind the secondary jet the pressures generally are less than the static pressure of the undisturbed flow over a relatively large area. This reduced pressure tends to decrease the side force associated with the secondary-jet injection.

An examination of available pressure-distribution measurements over a flat plate immersed in an airstream and having a gas jet exhausting normal to the plate indicated that the side force could be increased appreciably if the area of the low-pressure regions could be reduced or eliminated. However, available data did not appear to be sufficiently comprehensive to assess the gain to be made by reduction in area of the negative-pressure regions. The present study, therefore, was undertaken to provide additional data for such an assessment as well as to provide some additional data on the relative merits of sonic and supersonic secondary jets. Some results for sonic and supersonic secondary nozzles exhausting normal to a flat plate are given in references 2, 5, 7, and 8 and results for secondary nozzles in conjunction with primary nozzles are presented in references 1 and 6. The present investigation involved the determination of the pressure field on a sharp-edged splitter plate in a supersonic stream with a sonic or a supersonic jet exhausting normal to the plate. The tests were conducted at a free-stream Mach number of 4.5 at Reynolds numbers per foot from 1.9×10^6 to 5.3×10^6. Secondary-jet total pressure was varied from 200 to 600 lb/sq in. gage, corresponding to jet pressure ratios from 680 to 5,790.

SYMBOLS

A_e exit area of secondary jet

C_p pressure coefficient, $(p - p_\infty)/q_\infty$

F reaction force of fully expanded nozzle, $\dot{m}V_e$

F_c reaction force of isolated jet, $\dot{m}V_e + \left(p_e - p_\infty\right)A_e$

F_t total force, that is, reaction force plus induced force

M Mach number

$\dot{m}$ mass flow of secondary jet, slugs/sec

p static pressure

p_e exit pressure of secondary jet

p_t total pressure

p_∞ free-stream static pressure

q dynamic pressure

R radius

V_e exit velocity of secondary-jet flow

Subscripts:

j jet

∞ free stream

APPARATUS AND PROCEDURE

A sketch of the flat plate used in the investigation is given in figure 1. The locations of the pressure orifices with respect to the jet are given in figure 2. Although the plate pressures were measured on both sides of the plate center line, the data are plotted as if measured on one side. Several of the orifices were found to be plugged or leaking and therefore the pressure coefficients for those orifices are not presented. The flat plate was sharp edged and was mounted to the tunnel wall with four double-wedge struts. The upper surface of the flat plate was about 11 inches above the tunnel wall.

Two secondary-jet nozzles were used, a sonic nozzle with an exit diameter of 0.600 inch and a Mach number 4.5 supersonic nozzle with a minimum diameter of 0.307 inch and an exit diameter of 1.25 inches (area ratio 16.56). A sketch showing the details of the nozzles is included as figure 3. In each case the secondary jet was located on the plate center line $14\frac{3}{4}$ inches from the apex (fig. 1) and was flush with the plate surface.

Scanner valves were used in conjunction with automatic punchcard equipment to record the pressures on the plate. Repeatability of the test data is indicated in figure 4.

The tests were conducted in the high Mach number test section of the Langley Unitary Plan wind tunnel at a Mach number of 4.5. The stagnation pressure was varied from 30 lb/sq in. to 85 lb/sq in. for a range of Reynolds numbers per foot from 1.9×10^6 to 5.3×10^6.

The tunnel pressurized cold-air supply was used to obtain the secondary jet air; the stagnation temperature of this secondary jet air varied from 60° F to 78° F. The secondary-jet total pressure was varied from 200 to 600 lb/sq in. gage.

RESULTS AND DISCUSSION

Center-Line Pressure Distributions

The differences between the pressures obtained on the plate with the secondary jet on and the secondary jet off were determined and are presented on the figures in the form of the pressure coefficient C_p. The average of the values of C_p measured directly ahead of the secondary-jet exit (jet off) was assumed to be the average of values of C_p on the plate (jet off) and this average was used in obtaining the values of C_p which were plotted.

The pressure coefficients obtained along the plate center line are presented in figures 5 and 6 and show the effects of jet pressure ratio on pressure coefficients. In general, the figures show high positive pressure coefficients ahead of both the subsonic and supersonic jets, and relatively small negative pressure coefficients behind the jets at the plate center line. For the supersonic jet the high pressures ahead of the jet decreased rapidly with increase in distance ahead of the jet.

The ratio of secondary-jet total pressure to free-stream static pressure $p_{t,j}/p_\infty$ had no appreciable effect on the pressure distribution behind the secondary jet (figs. 5 and 6). Upstream of the jet, however, increasing the pressure ratio generally increased the pressure coefficients on the plate. This effect was more pronounced for the sonic jet than for the supersonic jet. It should be noted that for the supersonic jet the effect of pressure ratio on pressures ahead of the jet is greater at higher Reynolds numbers than at lower Reynolds numbers. (See figs. 5(a) and 5(b).) This appears to be opposite to the effect obtained with the sonic jet. (See figs. 6(a) and 6(b).)

It should also be pointed out that although the type of boundary layer on the plate was not determined in the present investigation a number of references, such as reference 7, indicate that the condition of the boundary layer may have a large influence on the resulting pressure distribution.

Pressure Distribution Contours

The data presented thus far were obtained along the plate center line. Pressures also were measured over a large area of the plate. These pressures are shown in figures 7 and 8 for the supersonic and sonic nozzles, respectively, as contours of constant pressure coefficient. The negative pressure coefficients ahead of the jet (fig. 7(a)) are believed to result from local flow disturbances and to have no significant effect on the results of this investigation. The plots are presented for several values of jet pressure ratio $p_{t,j}/p_\infty$ and a free-stream

Reynolds number of 5.3×10^6. The charts were used to determine the induced force normal to the plate. These induced pressure forces were then added to computed secondary-jet reaction forces to obtain the total force normal to the plate.

The force induced on the flat plate due to jet interference is presented in the following table for several values of jet pressure ratio and for a free-stream Reynolds number of 5.3×10^6.

$p_{t,j}/p_\infty$	Induced force, lb	
	Sonic secondary jet	Supersonic secondary jet
680	25.4	7.4
1,360	38.3	12.9
2,055	45.7	19.3

These values are positive as were those obtained in tests of a flat plate reported in reference 5 and in tests of nozzles reported in references 1 and 6 and are in contrast with the negative values obtained in reference 8. The reason for the negative values of reference 8 is not readily evident, but may be due to the differences in test conditions.

Total Force Normal to Plate

There were two primary points of interest in the present study. The first was the determination of the relative merit of a sonic and supersonic secondary jet by measurement of the jet-interaction effects of each on a complete flat plate, and the second was the benefit which might be realized if the plate were cut to eliminate regions of negative pressure. An estimate of this benefit was obtained by assuming that the plate was cut along the free-stream static-pressure line $C_p = 0$ and using only the area upstream of this line in computing induced pressures. As a matter of interest, applying a similar procedure to the application of a secondary injection nozzle to a rocket motor would result in cutting the motor expansion section to a tulip shape having the same number of "petals" as there are secondary jets. It is necessary to assume here that ambient conditions would not affect rocket nozzle characteristics to a great extent.

There are a number of comparisons that can be made to show force magnification resulting from jet-interference effects. Most previous studies have shown these effects by comparing the total normal force F_t with that computed for the corresponding isolated jet F_c. The term isolated jet is used herein to mean a jet used in the usual manner to provide a pure reaction force. On the basis of such a comparison, the effects of sonic secondary-jet interference showed a rather high percentage of benefits; however, this basically amounts to obtaining a large percentage of benefit over a reaction system that is relatively poor for the mass flow expended.

In the present study the effects obtained from jet interaction for both the sonic and supersonic jets are evaluated by comparison with an isolated reaction jet designed for maximum efficiency. In other words, comparison is made with a fully expanded supersonic jet sized to accommodate the same mass flow as the test jets.

The results of such a comparison are shown in figure 9. The curves show the ratio of the total reaction force of the test jet to the calculated reaction force F of an isolated fully expanded jet, plotted as a function of pressure ratio $p_{t,j}/p_\infty$.

It should be pointed out that for the test conditions considered, the supersonic fully expanded nozzle would operate at a Mach number between 5.2 and 6.2, depending on the pressure ratio $p_{t,j}/p_\infty$. (See top of fig. 9.)

The results of figure 9 show a number of interesting points. Over most of the pressure-ratio range the total reaction force obtained with the sonic secondary jet and reaction plate was less than that computed for an isolated fully expanded supersonic jet having the same pressure ratio. Eliminating the areas of negative pressure on the plate (then referred to as the cut plate) resulted in a sufficient increase in total reaction to make the sonic jet better than an isolated fully expanded jet for the lower values of test pressure ratio. With the assumed cut plate, the results indicate that the sonic-jet system would yield from 95 to 117 percent of the normal force of fully expanded isolated nozzles. The results obtained with the supersonic reaction jet ($M = 4.5$) are somewhat better than those obtained with the sonic jet. The results show that the combination of the $M = 4.5$ jet and the actual flat plate yields from about 22 to 27 percent more normal force than that computed for fully expanded isolated reaction jets. A further increase of about 12 percent is indicated for a cut plate. These percentages are approximate for the test pressure-ratio range. The data show some variation with pressure ratio, with the benefits of jet interaction increasing as the pressure ratio is reduced. These data and the data of reference 5 are again in contrast with those of reference 8. In general, based on a comparison of the ratio of the total reaction force of the test jet to the calculated reaction force of an isolated fully expanded jet (with mass flow equal to that of the test jet), the supersonic nozzle appears to be more effective for use as a control than the sonic nozzle. Total force as used herein is the calculated simple reaction force of an isolated nozzle plus the induced force resulting from the secondary-jet interference with the stream flowing over the flat plate.

CONCLUDING REMARKS

An investigation was made to determine the pressure distributions on a flat plate with a sonic or a supersonic jet exhausting normal to the plate surface. Tests were made at a Mach number of 4.5 for a range of jet pressure ratios (that is, ratio of stagnation pressure of secondary jet to free-stream static pressure) and for various free-stream Reynolds numbers.

Based on a comparison of the ratio of the total reaction force of the test jet to the calculated reaction force of an isolated fully expanded jet (with mass flow equal to that of the test jet), the supersonic nozzle appears to be more effective for use as a control than the sonic nozzle. Total force as used herein is the calculated simple reaction force of an isolated nozzle plus the induced force resulting from the secondary-jet interference with the stream flowing over the flat plate.

The data also indicate that eliminating areas of negative pressure on the plate would cause an increase in effectiveness up to approximately 12 percent for either jet.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 6, 1963.

REFERENCES

1. Lingen, A.: Jet-Induced Thrust-Vector Control Applied to Nozzles Having Large Expansion Ratios. Rep. R-0937-33, Res. Dept., United Aircraft Corp., Mar. 1, 1957.

2. Cubbison, Robert W., Anderson, Bernhard H., and Ward, James J.: Surface Pressure Distributions With a Sonic Jet Normal to Adjacent Flat Surfaces at Mach 2.92 to 6.4. NASA TN D-580, 1961.

3. Hunter, Paul A.: An Investigation of the Performance of Various Reaction Control Devices. NASA MEMO 2-11-59L, 1959.

4. Vinson, P. W., Amick, J. L., and Liepman, H. P.: Interaction Effects Produced by Jet Exhausting Laterally Near Base of Ogive-Cylinder Model in Supersonic Main Stream. NASA MEMO 12-5-58W, 1959.

5. Amick, James L., and Hays, Paul B.: Interaction Effects of Side Jets Issuing From Flat Plates and Cylinders Alined With a Supersonic Stream. WADD Tech. Rep. 60-329, U.S. Air Force, June 1960.

6. Bankston, Lester T., and Larsen, Harold M.: Thrust-Vectoring Experiments With Gas Injection. NAVORD Rep. 6548, U.S. Naval Ord. Test Station, May 28, 1959.

7. Romeo, David J., and Sterrett, James R.: Aerodynamic Interaction Effects Ahead of a Sonic Jet Exhausting Perpendicularly From a Flat Plate Into a Mach Number 6 Free Stream. NASA TN D-743, 1961.

8. Janos, Joseph J.: Loads Induced on a Flat-Plate Wing by an Air Jet Exhausting Perpendicularly Through the Wing and Normal to a Free-Stream Flow of Mach Number 2.0. NASA TN D-649, 1961.

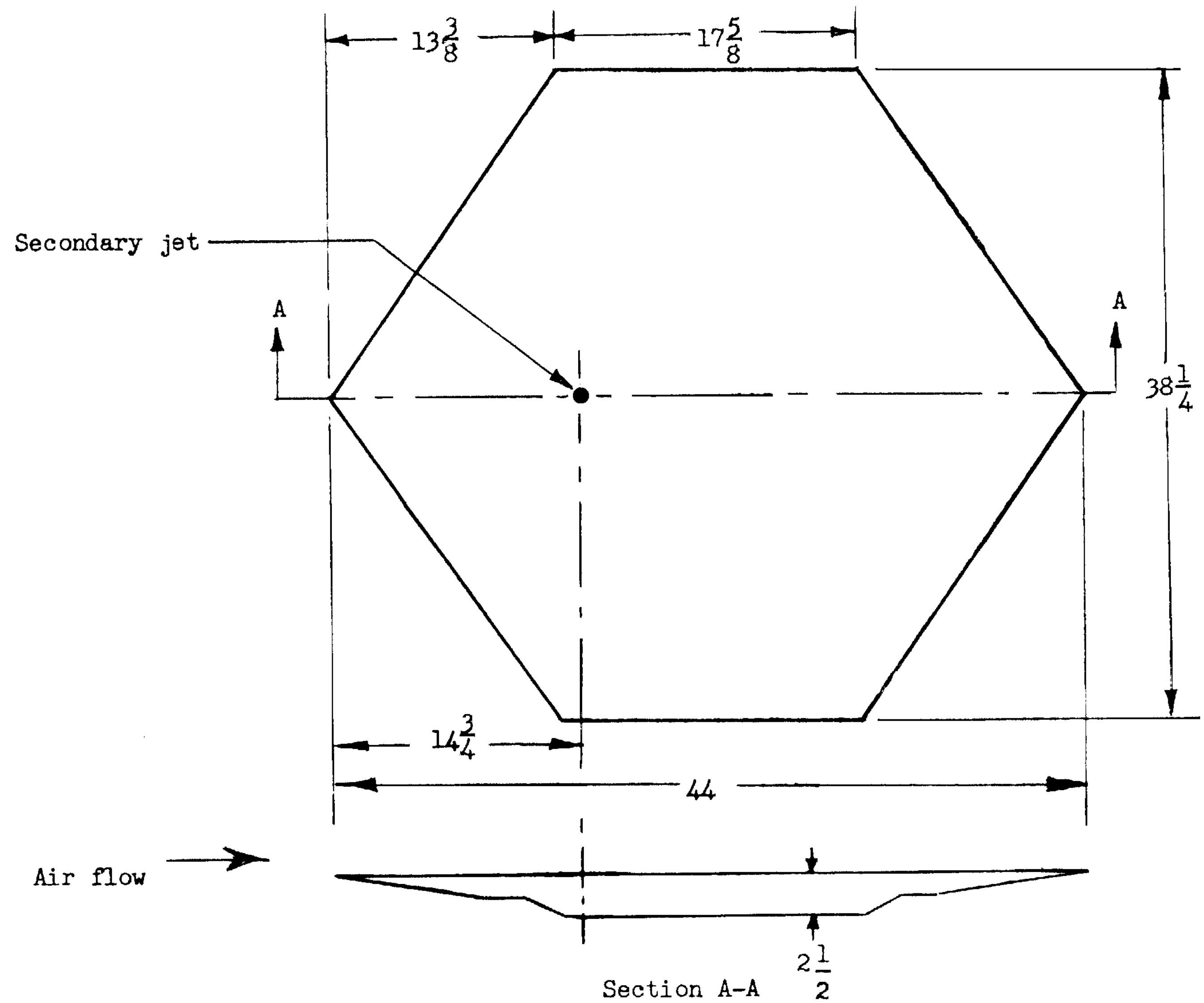
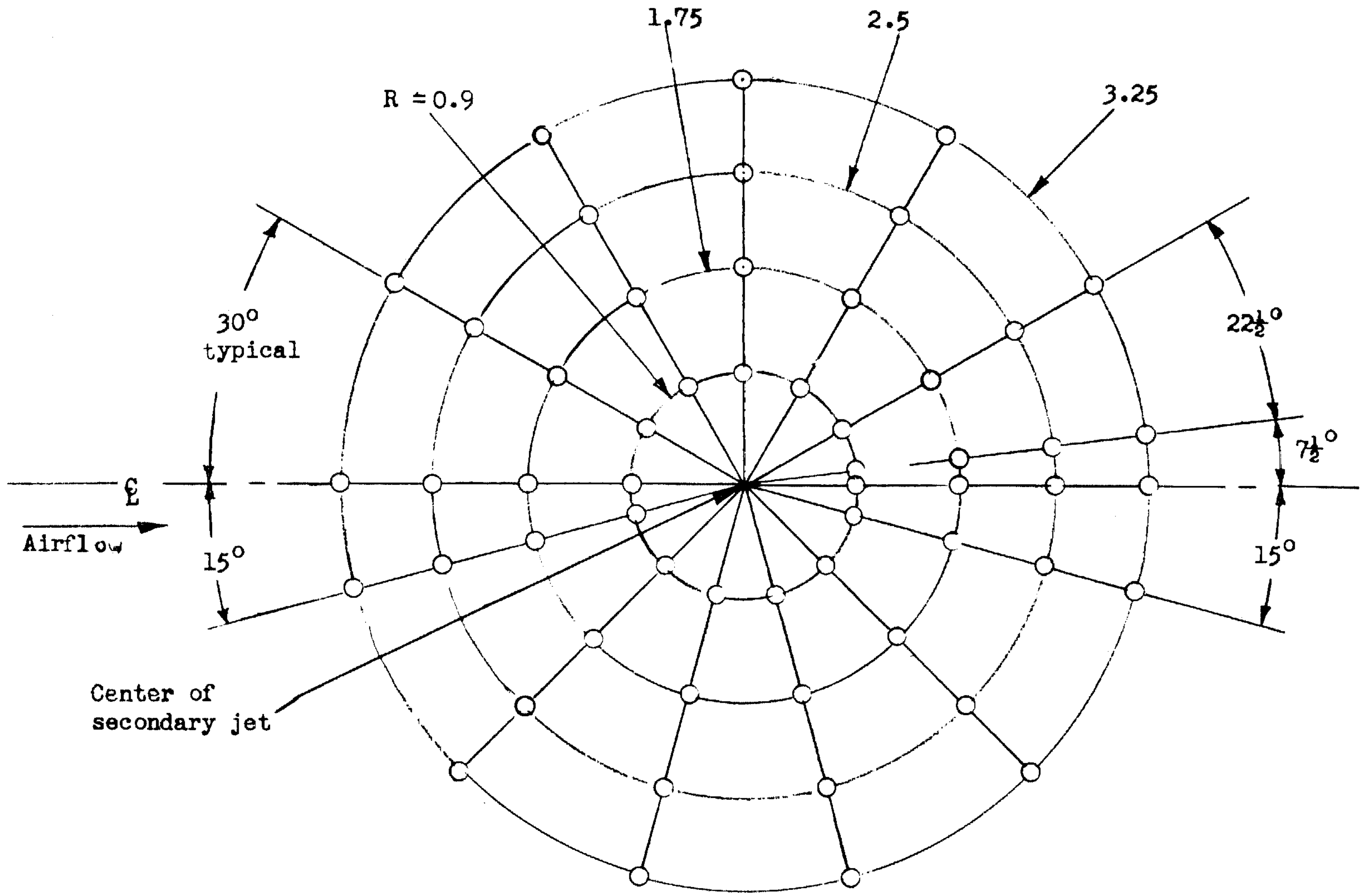
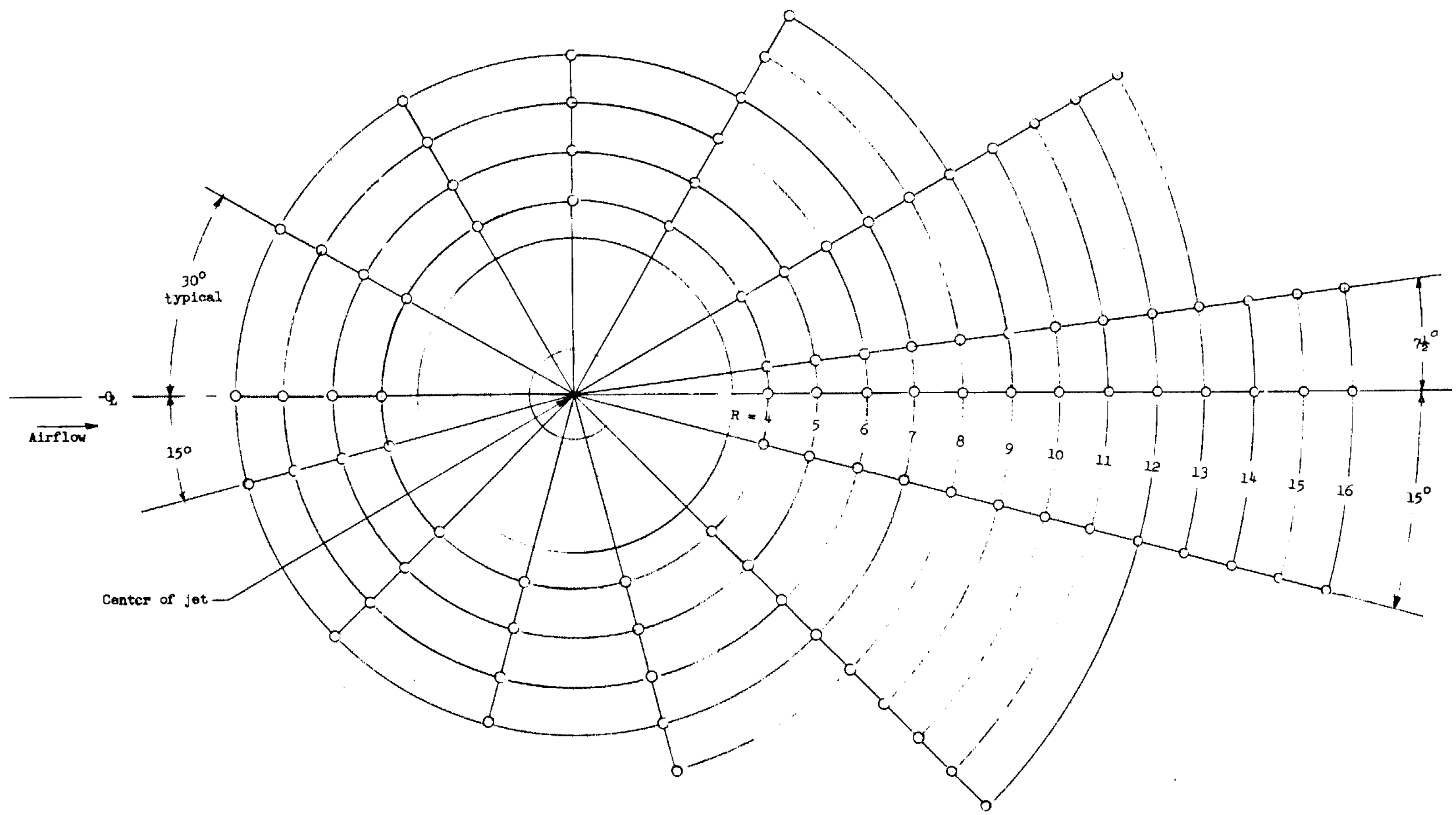


Figure 1.- Details of flat plate. All dimensions are given in inches.



(a) From R = 0.9 inch to R = 3.25 inches.

Figure 2.- Orientation of pressure orifices with respect to center of jet.



(b) From R = 4 inches to R = 16 inches.

Figure 2.- Concluded.

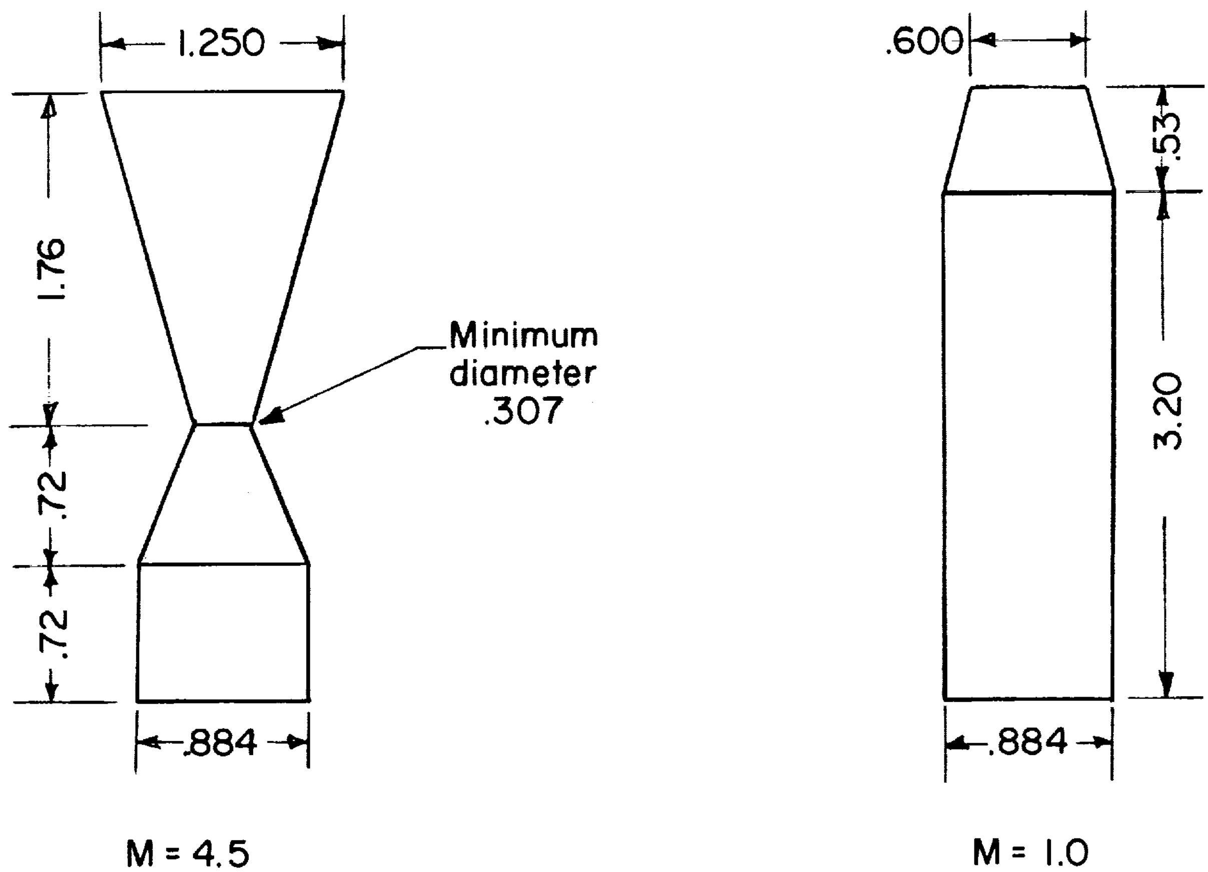


Figure 3.- Details of supersonic and sonic secondary nozzles. All dimensions are in inches.

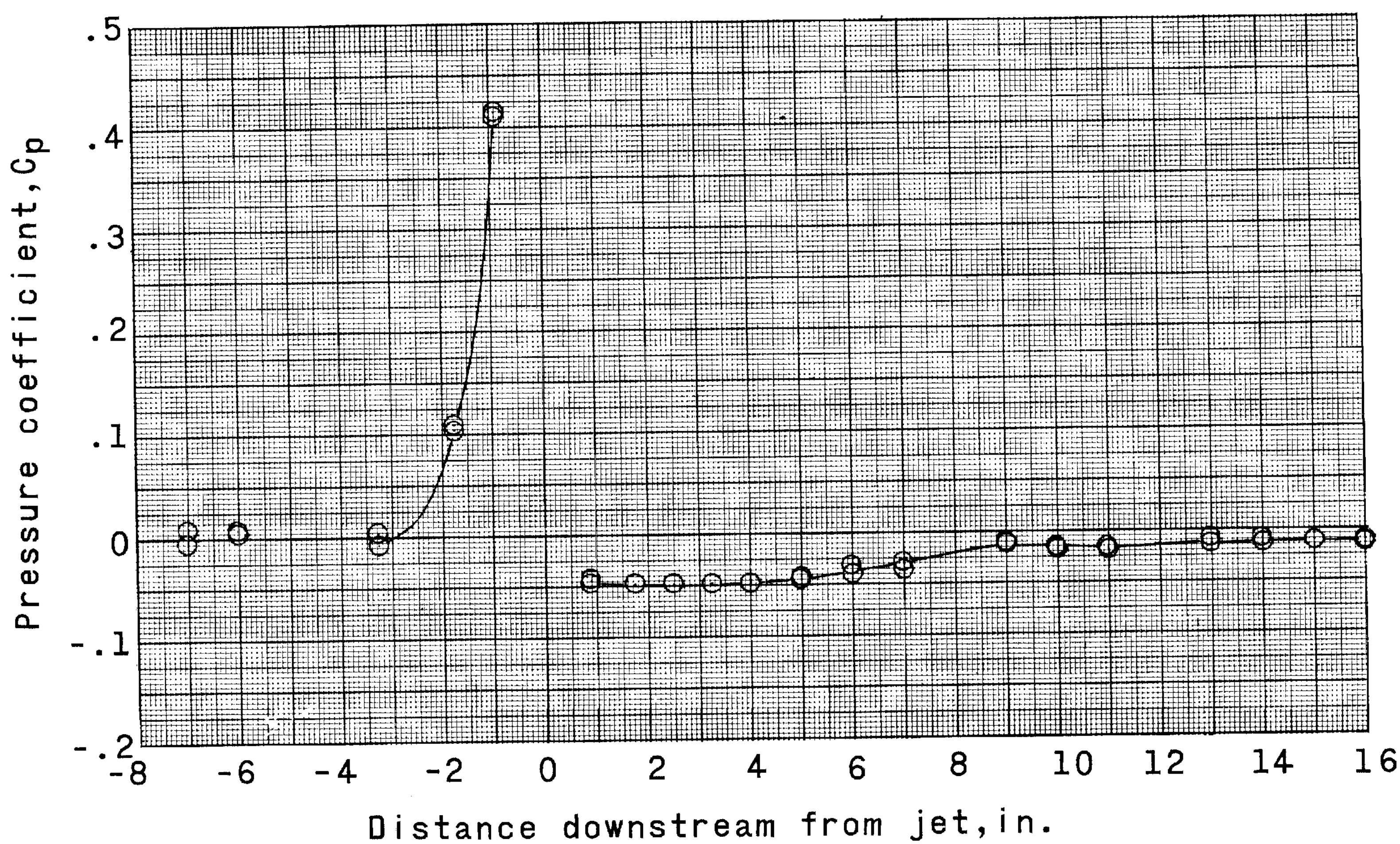
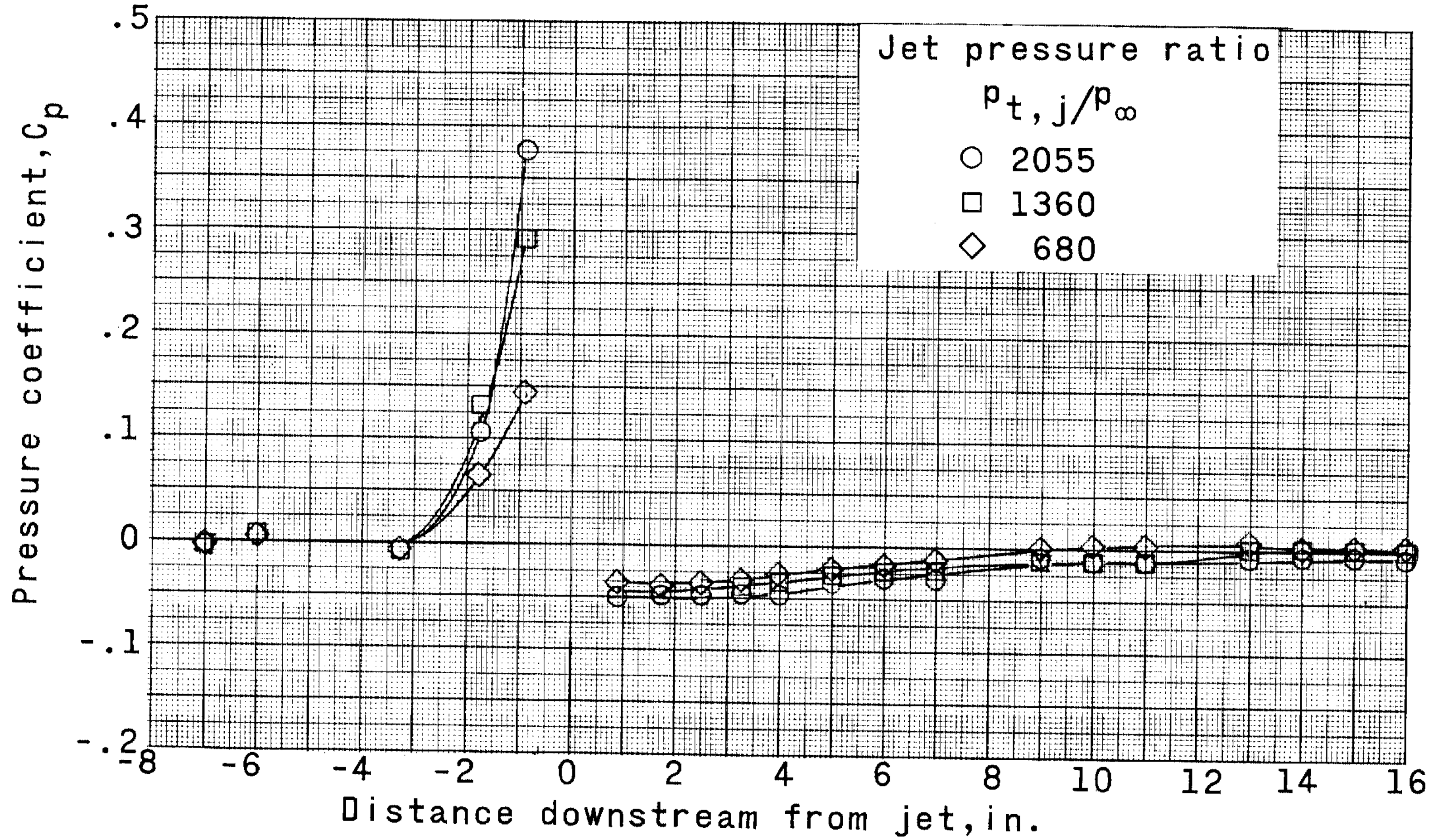
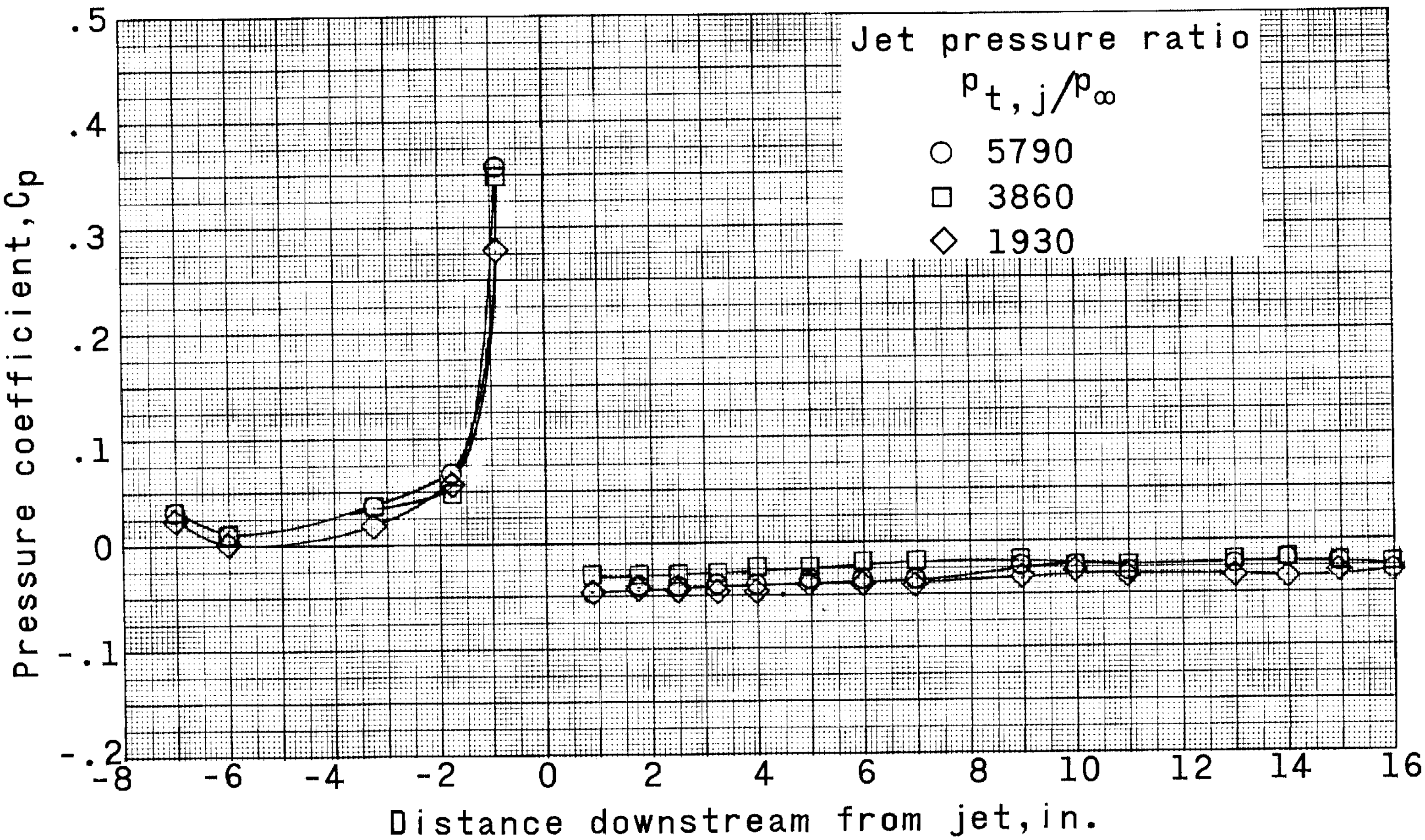


Figure 4.- Comparison of repeated measurements of center-line pressure distribution on flat plate. Supersonic jet; $p_{t,j}/p_\infty = 2{,}480$; Reynolds number per foot = 4.4×10^6.



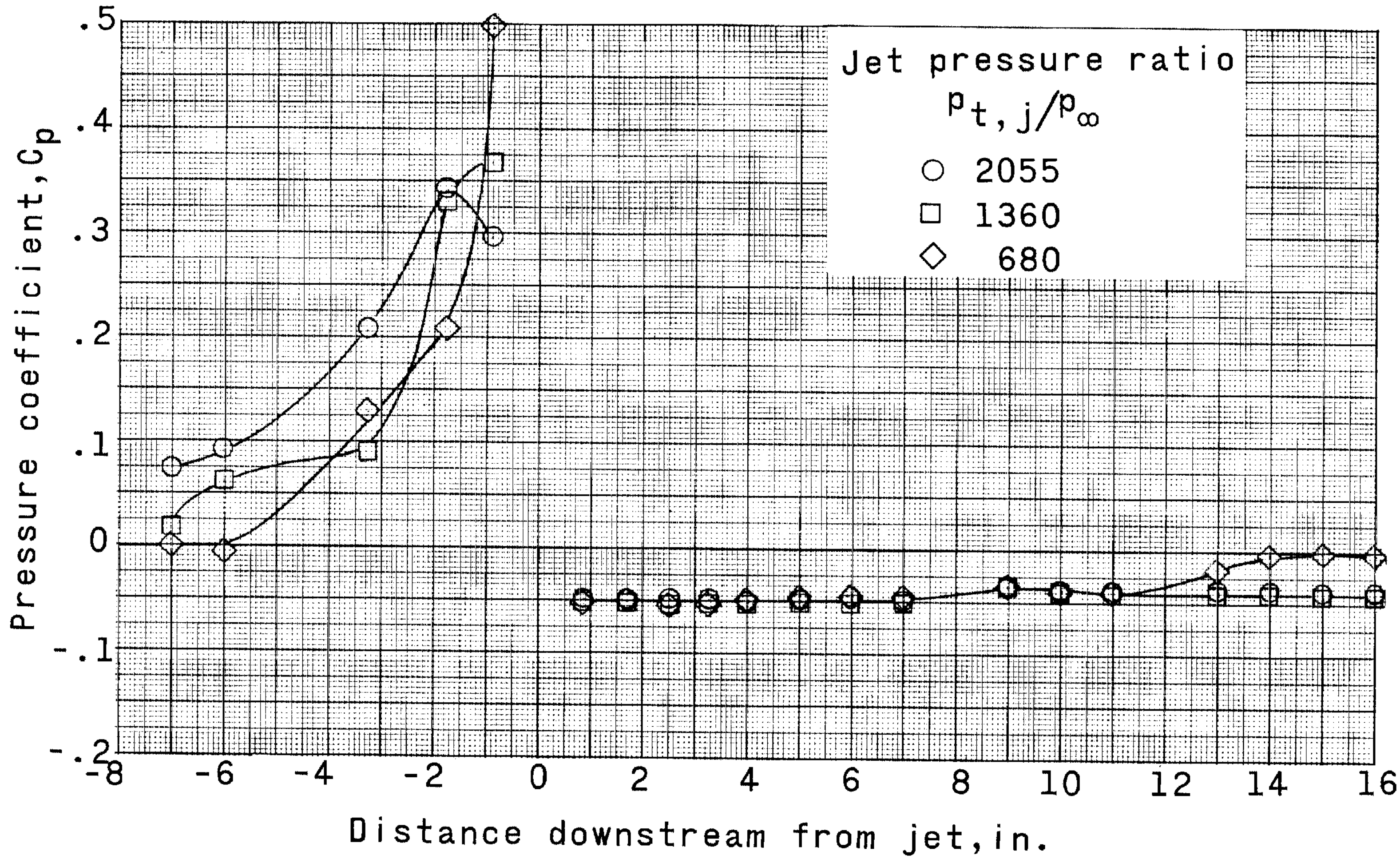
(a) Reynolds number per foot = 5.3×10^6.

Figure 5.- Effect of pressure ratio on center-line pressure distribution on flat plate. Supersonic jet.



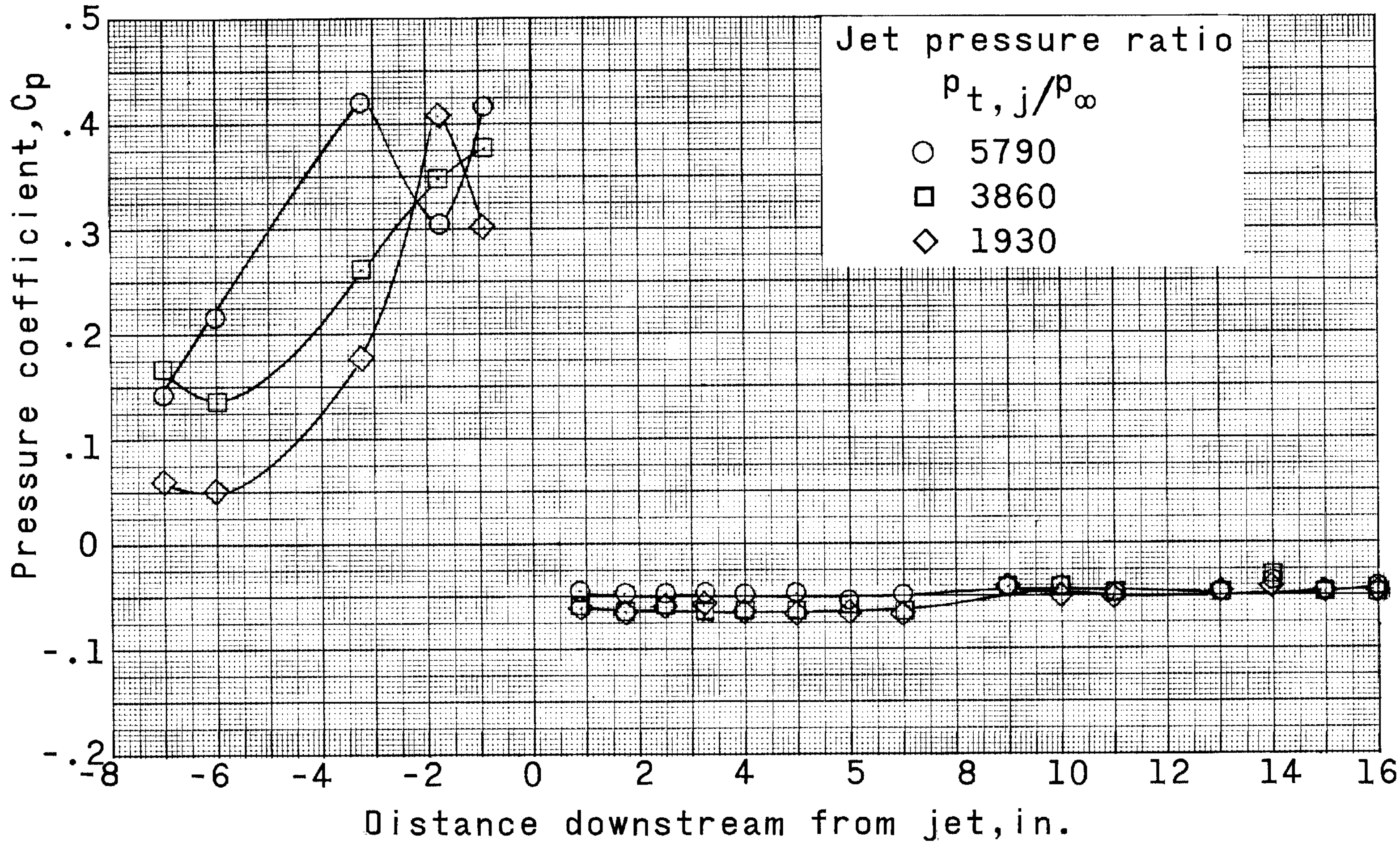
(b) Reynolds number per foot = 1.9×10^6.

Figure 5.- Concluded.



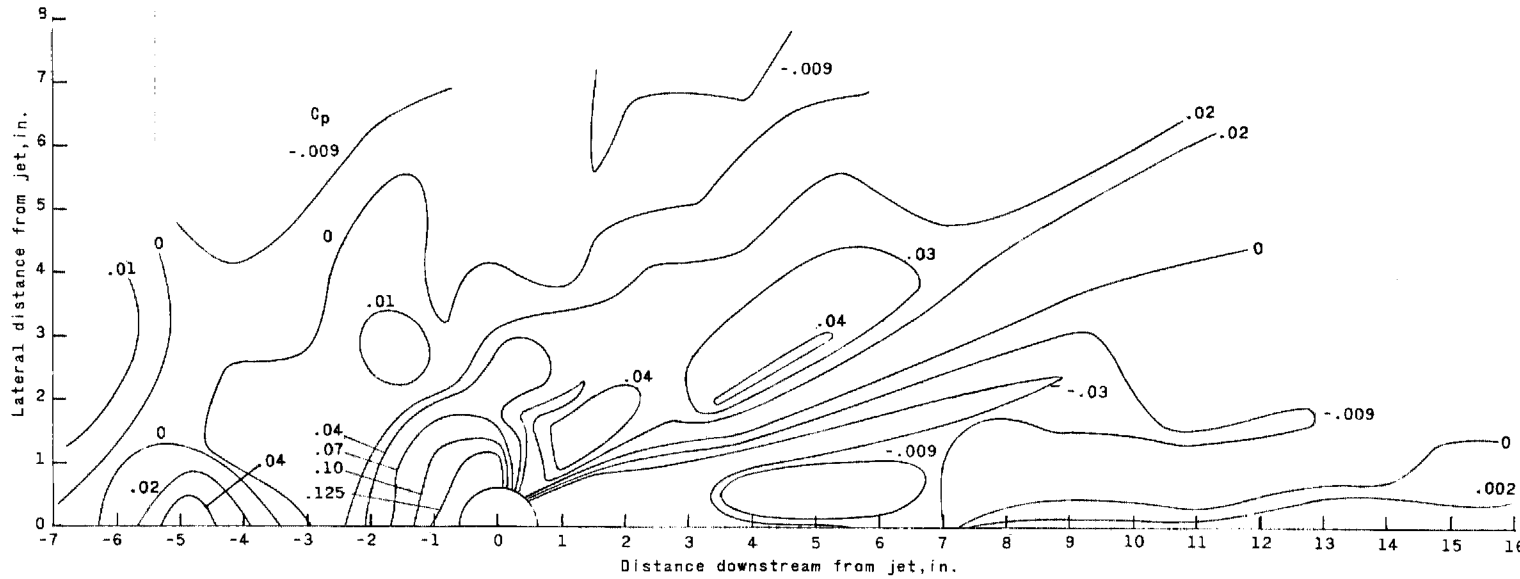
(a) Reynolds number per foot = 5.3×10^6.

Figure 6.- Effect of pressure ratio on center-line pressure distribution on the flat plate. Sonic jet.



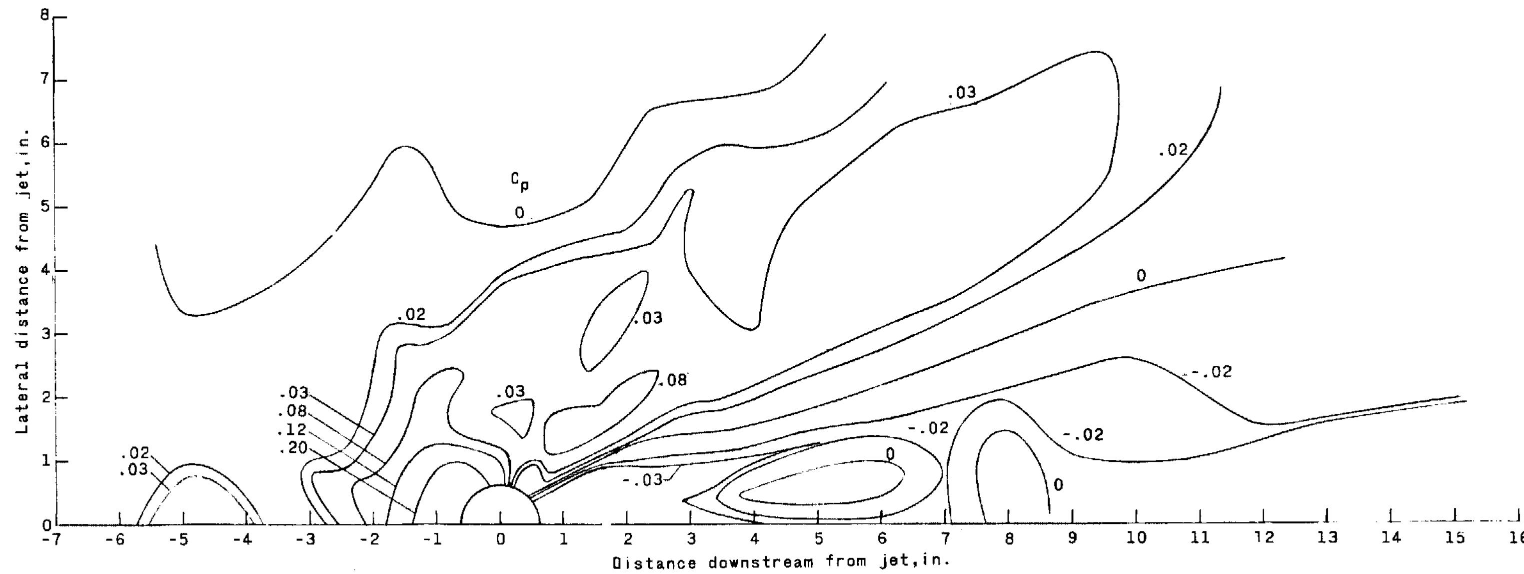
(b) Reynolds number per foot = 1.9×10^6.

Figure 6.- Concluded.



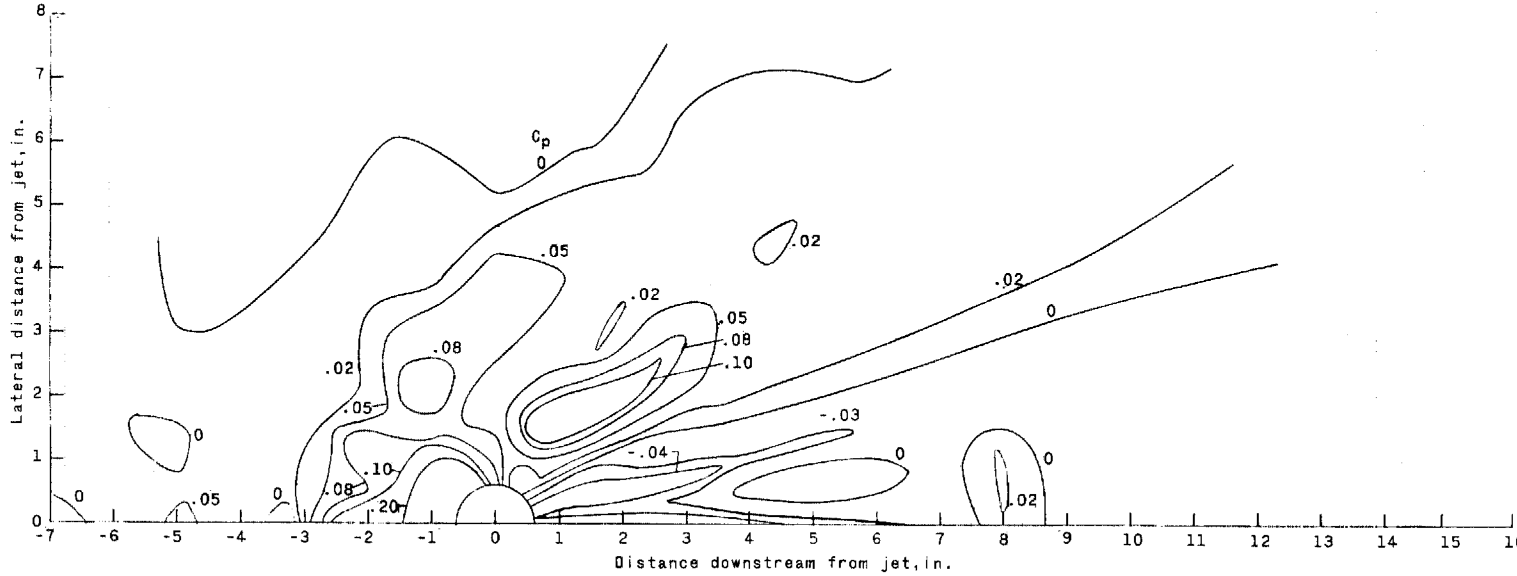
(a) $p_{t,j}/p_\infty = 680$.

Figure 7.- Contours of constant pressure coefficient on flat plate at Reynolds number per foot of 5.3×10^6. Supersonic jet.



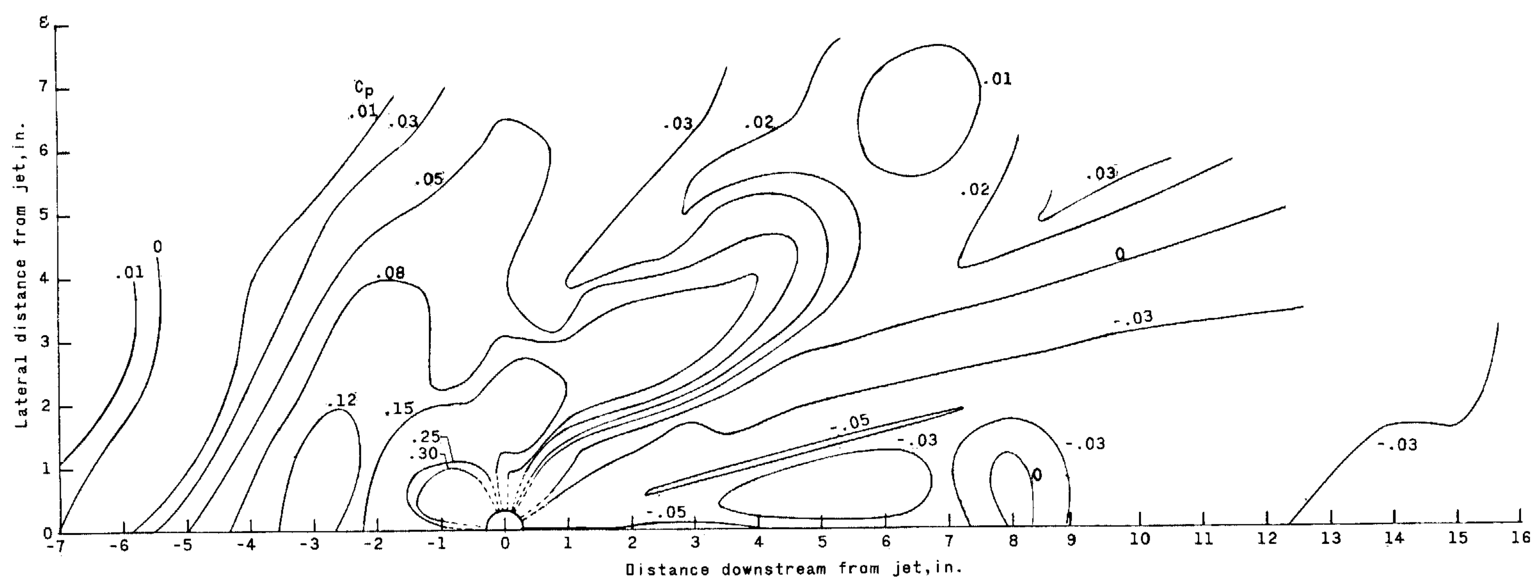
(b) $p_{t,j}/p_\infty = 1{,}360.$

Figure 7.- Continued.



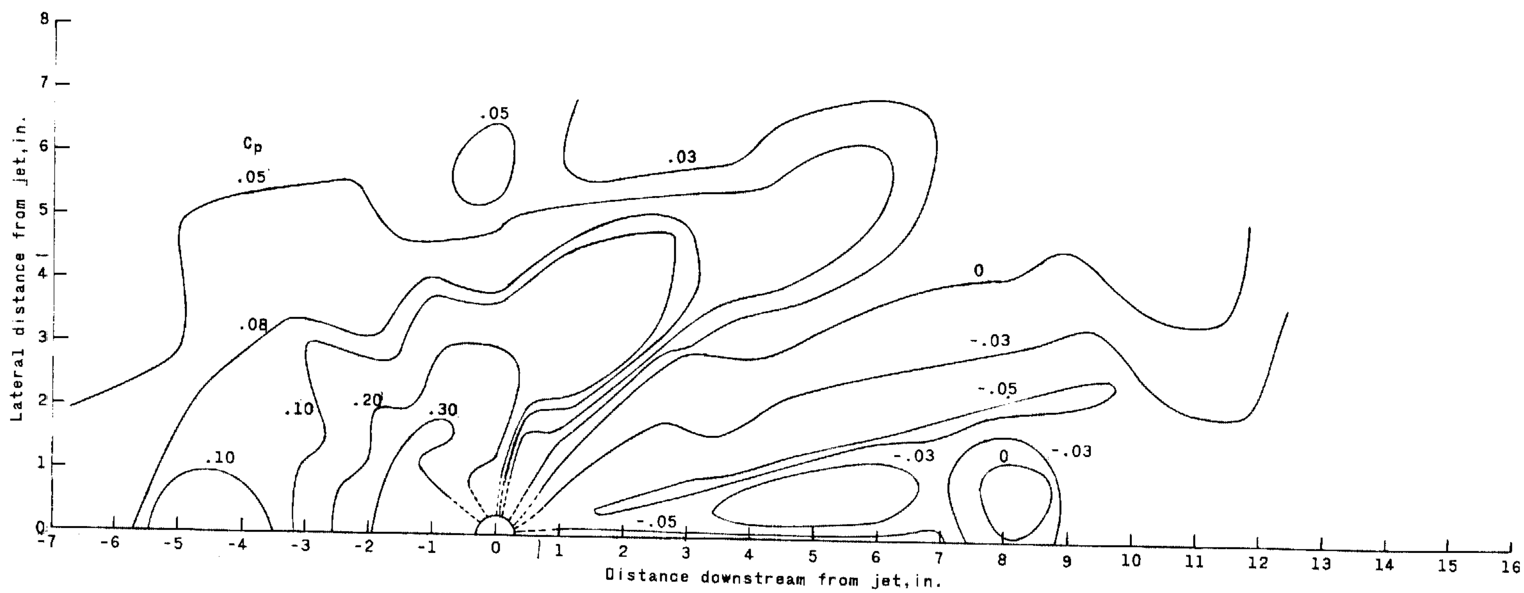
(c) $p_{t,j}/p_{\infty} = 2{,}055.$

Figure 7.- Concluded.



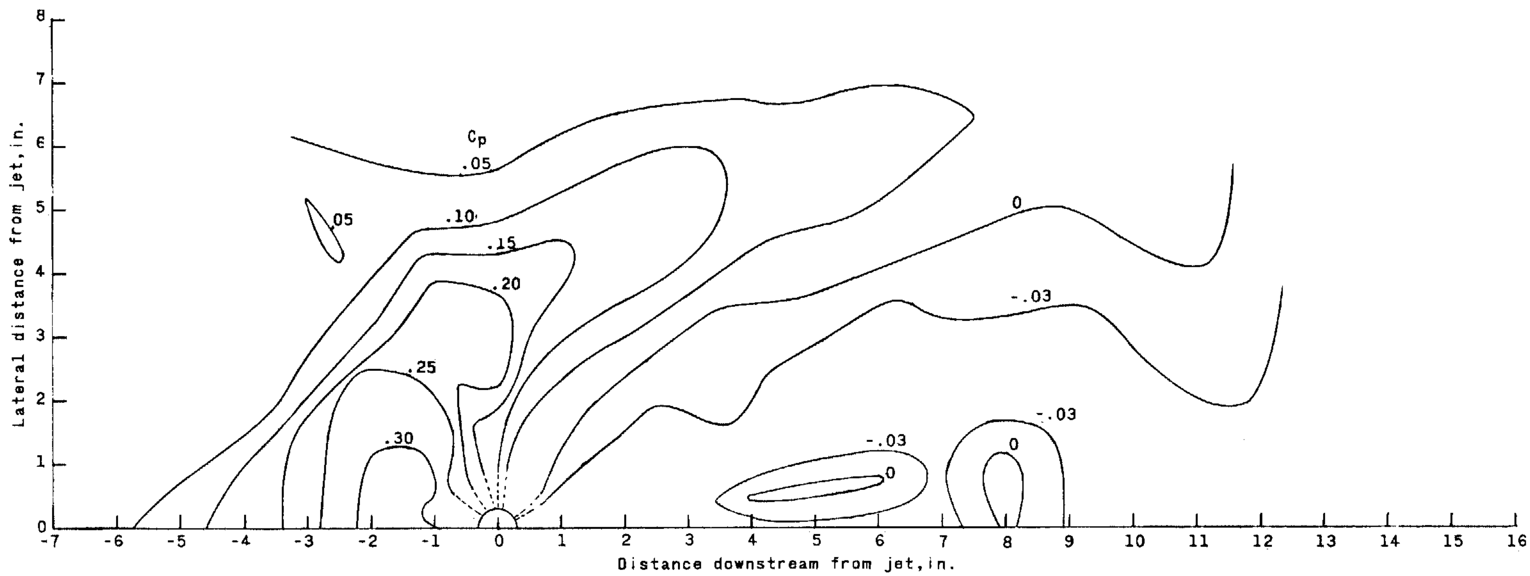
(a) $p_{t,j}/p_\infty = 680$.

Figure 8.- Contours of constant pressure coefficient on flat plate at Reynolds number per foot of 5.3×10^6. Sonic jet.



(b) $p_{t,j}/p_\infty = 1{,}360.$

Figure 8.- Continued.



(c) $p_{t,j}/p_\infty = 2{,}055$.

Figure 8.- Concluded.

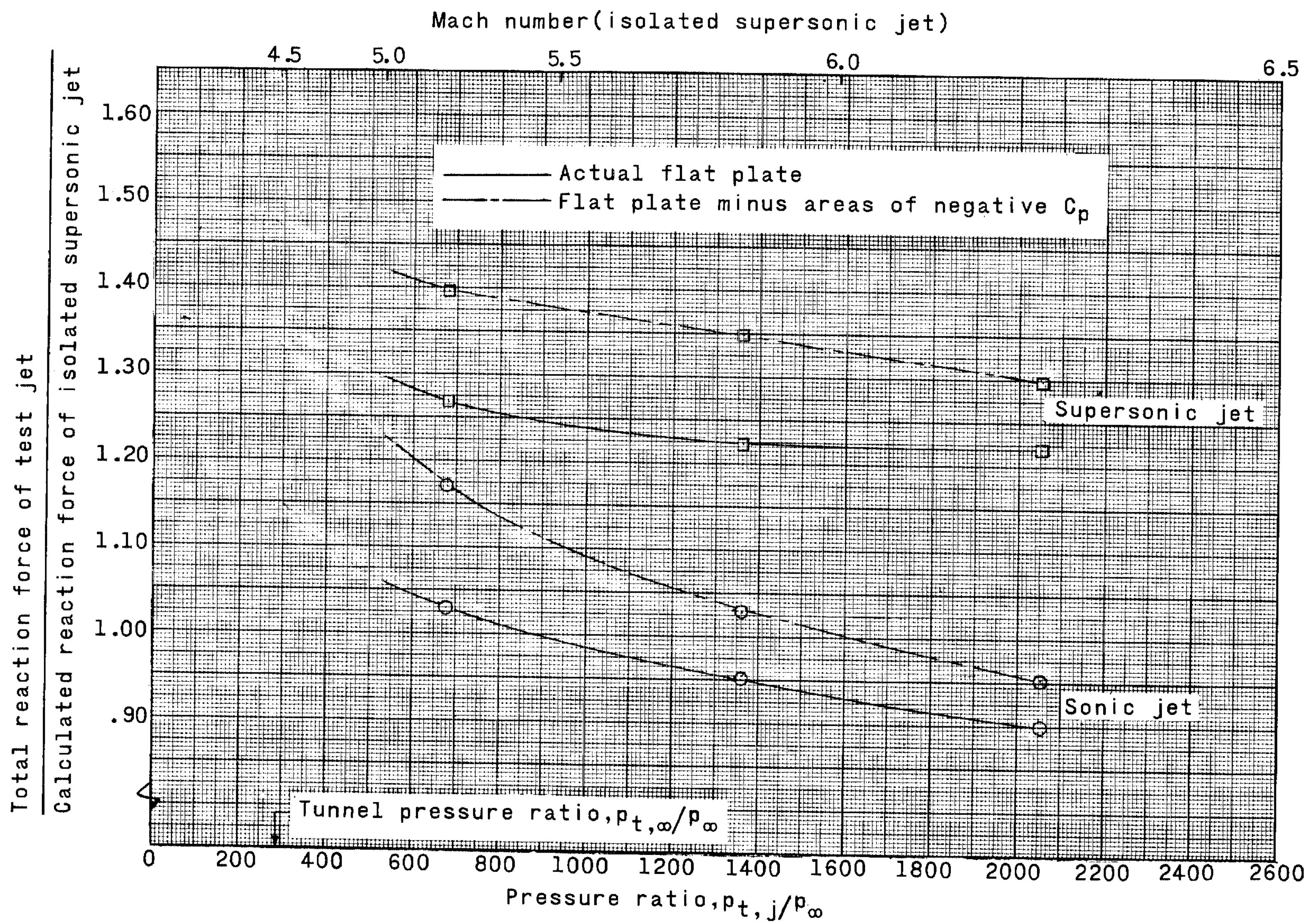


Figure 9.- Variation with pressure ratio $p_{t,j}/p_\infty$ of ratio of total reaction force of test jet to calculated reaction force of fully expanded supersonic jet of equal mass flow, showing effect of eliminating areas of negative C_p behind secondary jet.

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